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Stabilized hot electron bolometer heterodyne receiver at 2.5 THz

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We report on a method to stabilize a hot electron bolometer (HEB) mixer at 2.5 THz. The technique utilizes feedback control of the local oscillator (LO) laser power by means of a swing-arm actuator placed in the optical beam path. We demonstrate that this technique yields a factor of 50 improvement in the spectroscopic Allan variance time which is shown to be over 30 s in a 12 MHz noise fluctuation bandwidth. Furthermore, broadband signal direct detection effects may be minimized by this technique. The technique is versatile and can be applied to practically any local oscillator at any frequency. © *2012 American Institute of Physics*. [doi:10.1063/1.3688032]

Hot electron bolometer (HEB) mixers are currently the most sensitive heterodyne receivers above 1.5 THz,[1,2] with applications that include astronomical observations, atmospheric remote sensing, and imaging. However, when compared with other mixers such as Schottky diode and superconductor-insulator-superconductor (SIS) receivers,[1] HEBs suffer from inferior stability.[3] This ultimately places undesirable constraints on observation strategies. Astronomical sources, in particular, are often weak with the signal deeply embedded in the noise, requiring long integration periods. Improvement in the HEB mixer intermediate frequency (IF) stability is possible through use of synchronous detection or spectroscopic treatment of the receiver output signal.[4] Although effective, these methods do not address the cause of HEB receiver instability. This work arose from a desire to show that HEB instability is predominantly the result of external factors such as the fidelity of the local oscillator (LO) signal and mechanical modulation of the LO-mixer standing wave.

The HEB consists of a superconducting thin film that bridges two normal metal contacts. These contacts also form part of an antenna for quasi-optical coupling of radiation into the device by means of a high resistivity Si lens. A combination of both electrical bias and LO optical pumping maintains a temperature distribution of hot electrons across the superconducting bridge producing a resistive state region in the center of the bridge.[5] Modulation of this resistance at the IF occurs as a result of heterodyne mixing. Any change in total incident power will therefore directly influence mixer performance parameters, such as conversion gain, output noise, and IF bandwidth.

Total power dissipated in the bridge, P_{total}, is equal to the sum of the absorbed LO power P_{LO}, the power induced by the bias voltage P_{bias}, and the absorbed optical signal P_{signal}. Since P_{signal} is, in general, small relative to P_{LO} and even negligible in the case of a relatively large HEB operated with a high P_{LO}, and the bias supply voltage is internally stabilized, fluctuations in the LO power will be the dominant source of potential instability. Without correction, any drift in LO power can accumulate with time so that the device no longer operates in the same state. This drift is also problematic over longer timescales in terms of instrument calibration.

Several studies have reported on the stability of HEB receivers.[6–10] Balanced waveguide HEB mixers have demonstrated improved stability[11] but at the expense of complex device design and fabrication. Furthermore, it has been shown that it is possible to stabilize an HEB mixer by stabilizing the amplitude of a far infrared (FIR) gas laser LO by adding electrical feedback to its CO_2 pumping laser.[12] An alternative method uses injection of an additional microwave source at a frequency outside of the device band gap as a means of adjusting HEB incident optical power.[13] These methods have all demonstrated improved stability with varying success; however, they are either tailored to a particular LO source or require modification to the IF chain.

In a different approach to this problem, we utilize the HEB mixer direct detection sensitivity. This is possible as the DC bias and AC IF signal are separated by a bias-T. It is straightforward, therefore, to use a single HEB device as both a heterodyne mixer and a direct detector simultaneously and independently. When a variable optical attenuator is placed in the LO beam path, a hardware proportional-integral-differential (PID) controller may then be used to provide real time feedback and henceforth stabilization of the HEB absorbed LO power. A common method for adjusting the incident LO power, for example, in Y-factor measurements,[14] is the rotation of a plane polarizer placed in the beam. Early attempts at HEB stabilization utilized PID control of a polarizer grid driven by a stepper motor. Although this approach showed clear improvement in HEB stability, the speed, angular resolution, and dynamic range of the polarizer grid movement limited the effectiveness of the feedback loop. However, using an alternative approach, we show that a swing-arm voice coil actuator[15] can be used as a very effective variable optical attenuator since it is fast, with

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high resolution and full dynamic range. The actuator demonstrated here can be adjusted within a frequency band 0-200 Hz (mechanical limitation) to interrupt any percentage of the LO beam by varying its angle as a function of applied current.

In the stabilized mode of operation, the HEB bias current becomes the set point for the PID loop and is maintained through rapid correction of the LO intensity. This has the effect of significantly reducing multiple instability sources including LO amplitude, atmospheric turbulence in the LO path, and LO mechanical instability.

Since only the incident total power of the LO is important, changes to the LO beam shape caused by interruption of the beam have no negative effects on mixer performance. To verify this, receiver noise temperature has been directly measured with a single HEB using both a rotating polarizer (where the LO beam shape is conserved) and a swing-arm actuator (where the beam is clipped) with identical results. Furthermore, the Y-factor can now be measured directly using a swing-arm actuator without the need for a polarizer grid.

To quantify the effectiveness of the stabilization method, we use Allan variance measurements[16] in two configurations: total power (continuum) and spectroscopic (spectral differential). Allan variance is a well-known tool for measuring and characterizing the stability of a system. It is known that random, white noise integrates down with time as $T^{-1/2}$ according to the radiometer equation.[17] The finite stability of a real system eventually deviates from the radiometer equation at an integration time known as the Allan variance minimum time. The quoted system Allan time thus relates to the maximum usable integration time for a given bandwidth.

In the literature, HEB Allan times are often quoted at different bandwidths and referred to only by IF signal bandwidth. However, due to time inefficiency in power meter sampling and power meter internal noise contribution, an effective noise fluctuation bandwidth is actually measured.[18]

A schematic of the setup describing the Allan variance measurement is shown in Figure 1. In this study, we use a NbN mixer with an HEB area of $0.4 \times 4\,\mu m^2$, which requires a P_{LO} of 480 nW and a P_{DC} of 35 nW for its optimal operating.[19] This device is attached to a Si lens which is mounted in a mixer block on the 4.2 K stage of a liquid He cryostat

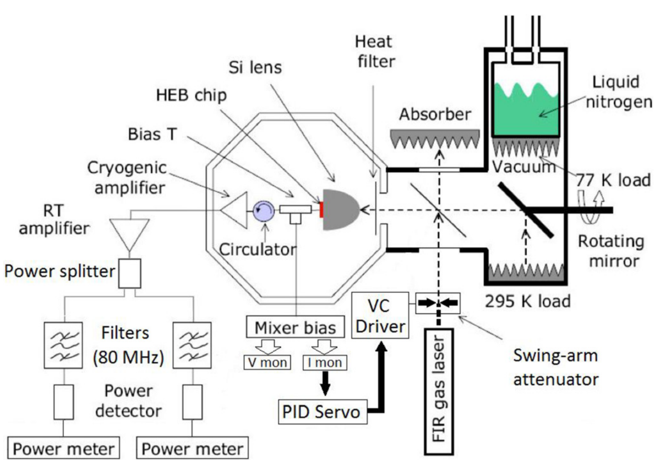

FIG. 1. (Color online) Schematic of the dual channel experimental setup for spectroscopic Allan variance measurements.

(see Fig. 1). The local oscillator is an FIR gas ring laser that is tuned to the 2.523 THz methanol line. The broadband blackbody sources at room temperature and 77 K, together with a 3 μm thick mylar beamsplitter, share a common vacuum enclosure with the mixer. This setup not only reduces signal optical loss but also eliminates instability due to the microphonic vibration in the thin beam splitter.

The IF signal is first amplified by a Berkshire 1-2 GHz cryogenic amplifier and then further amplified by two MITEQ room temperature amplifiers before being filtered by an 80 MHz bandwidth (−3 dB) tunable 1-2 GHz bandpass filter (verified independently). To derive the total power instrumental stability, the IF signal is sampled by a fast Agilent E4418B power meter. In the spectroscopic (dual channel) configuration, the IF signal is split after the first room temperature amplifier using a power splitter. The parallel IF signals are then filtered (80 MHz) and fed to two identical (Agilent E4418B) power meters. A channel separation of 500 MHz is used in spectroscopic mode with filters set to 1.25 GHz and 1.75 GHz. IF baseline removal is achieved using the method identified in Tolls *et al.*[20] Power meters are read out sequentially in a fast 200 samples/s mode, in which all power meter automated features and signal averaging/filtering are disabled. It should be noted that the reduced power present in the dual channel setup results in a smaller effective noise fluctuation bandwidth due to the noise floor limitations in the power meter described above. In all instances, at least 40 min of contiguous data is acquired for each Allan variance plot and the entire data set is used each time. Measurements were taken in a temperature controlled lab during the evening for optimum conditions. IF amplifiers were left to settle for several hours before beginning measurements, as was the FIR laser.

In order to independently assess the stability of the IF chain without noise contribution from the HEB, we first place the HEB in a fully superconducting state by applying no electrical bias or LO power. In this state, the IF amplifier chain is effectively in an input short mode. The recorded spectroscopic Allan variance in this state is very long at around 100 s in a 12 MHz noise fluctuation bandwidth. From this, we conclude that none of the components in the IF chain are significant sources of system instability.

Figure 2 shows the effectiveness of the stabilization technique by comparing unstabilized, stabilized, total power, and spectroscopic Allan variance at optimum bias and LO power. All data are collected using the dual channel setup described above. We therefore observe a consistent effective bandwidth across all data. For the unstabilized data, we observe a factor of ~10 difference between continuum and spectroscopic Allan times which is similar to that reported in the literature.[6] Application of the stabilization method yields a factor ~50 improvement in the total power Allan time. This results in a spectroscopic Allan time in excess of 30 s for a 12 MHz effective noise fluctuation bandwidth at optimum mixer bias. It is interesting to note that, as shown in the inset of Fig. 2, an Allan time of 25 s for a 12 MHz noise fluctuation bandwidth is observed for a small area HEB ($0.2 \times 2\,\mu m^2$) with a P_{LO} of 120 nW.[7] Furthermore, an additional advantage of this technique is that the signal direct detection effect due to broadband blackbody radiation, which

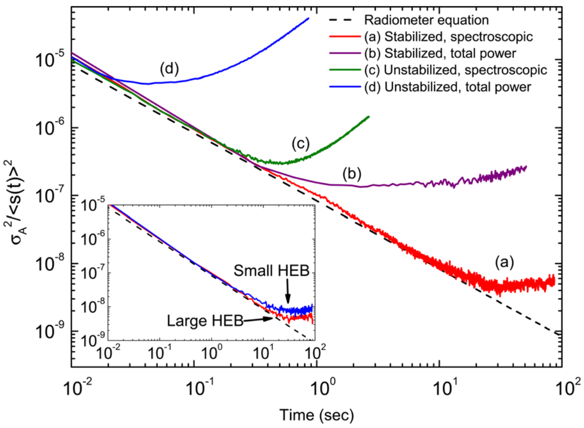

FIG. 2. (Color online) Measured (normalized) Allan variance curves using dual channel setup for large area HEB stabilized, unstabilized, total power, and spectroscopic configurations at optimum bias. In the inset, comparison of spectroscopic Allan variance for large area $0.4 \times 4\,\mu m^2$ and small area $0.2 \times 2\,\mu m^2$ HEBs. The radiometer equation for an effective noise fluctuation bandwidth of 12 MHz is shown in both plots.

is often problematic for small HEBs, may be mitigated since a constant bias state is maintained by the feedback loop.

Figure 3 shows the influence of bias voltage on HEB stability for both the stabilized and unstabilized cases. For the unstabilized case, stability is directly influenced by absorbed electrical power. As the voltage increases, the HEB becomes saturated. At very high bias, the HEB becomes almost fully resistive and thus the conversion gain becomes small with little sensitivity to LO power fluctuation, resulting in a long Allan time as expected. In contrast, with stabilization applied, the Allan minimum is approximately constant with bias voltage up to a few mV, suggesting that the LO is no longer the dominant source of instability. The stabilization scheme is not shown for the high bias case since the HEB direct detector sensitivity is also significantly reduced. Reduced direct detection sensitivity also occurs at low HEB bias. This is evident in Figure 3, where excess noise is present at the lower bias setting.

We attribute at least a part of the remaining instability to a noise limitation in our bias supply voltage and current monitor readout circuit. In this case, any error in the measurement of the HEB mixer current will cause the feedback loop to incorrectly adjust the LO power. That is, bias readout noise is transferred into LO intensity noise. The nature of this noise is likely to be 1/f, since it is caused by the relatively poor noise performance of output ground isolation amplifiers within the bias supply circuit. This is supported by the increased 1/f nature of the stabilized system which is visible in Figure 2. However, at this stage, it is difficult to differentiate between the relative contribution of bias supply noise and intrinsic HEB noise. The magnitude of the noise limitation has been estimated from power spectral density (PSD) measurements of the HEB voltage and current bias monitor outputs as shown in Figure 4. The data clearly show that the feedback loop removes a very large noise component and is effective up to about 200 Hz. It also shows 1/f noise present in the voltage monitor output. Using this data to characterize the readout noise, we estimate that the level of bias supply induced LO noise is around 25 dB below the level of non-stabilized LO noise (<10 Hz). An upgrade of our bias supply is expected to reduce current measurement noise and further improve the effectiveness of this stabilization method. If sufficient removal of instrumental instability could be achieved then it may be possible to use this technique to get a better understanding of the intrinsic stability of the HEB.

In summary, the application of a swing-arm actuator for rapid feedback LO intensity control is shown to improve the total power and spectroscopic Allan time of an HEB receiver by at least a factor of 50. We demonstrate Allan times of 30 s and 25 s for a 12 MHz noise fluctuation bandwidth for large and small area HEBs, respectively. These Allan times are notable given the particularly unstable pairing of a gas laser with an HEB. This method maintains the operating point of the HEB and thus stabilizes the mixer conversion gain and output noise, leading to longer Allan times. The enhanced stability afforded by the proposed technique will make astronomical observing routines such as "on the fly mapping (OTF)" significantly more efficient as fewer off source

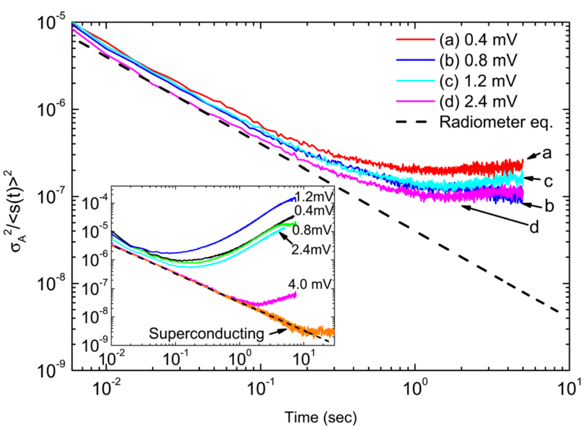

FIG. 3. (Color online) Measured (normalized) total power Allan variance using single channel IF setup. Stabilization is applied for several HEB bias voltages. The 0.8 mV curve represents optimum bias for this device. In the inset, measured total power Allan variance curves without stabilization applied. The radiometer equation for a noise fluctuation bandwidth of 25 and 30 MHz (see Ref. 18) is shown in the main and inset plots, respectively. All data sets are measured with a large area HEB.

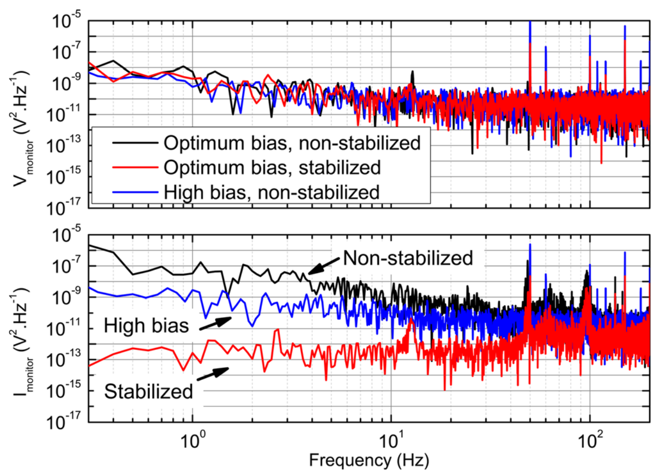

FIG. 4. (Color online) Power spectral density plots for HEB bias voltage monitor (upper panel) and current monitor (lower panel) outputs, with and without stabilization applied for a large area HEB. The HEB is constant voltage biased at optimum (0.8 mV) and with optimum LO power applied. In addition, data are shown for an HEB with high bias voltage applied (8 mV) to demonstrate the 1/f noise limitation of our bias supply readout circuit.

reference scans will be needed. The technique can be applied to practically any LO source and at any frequency.

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